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EVALUATION OF A PROTOTYPE BURNER FOR COMBINED NO_x/SO_2 CONTROL

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Sulfur Dioxide	Low-NOx Burners	
Burners		13A
Coal		21D
Combustion		21B

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ABSTRACT

This paper summarizes the results of EPA sponsored large pilot scale combustion tests on a Riley Stoker second generation low-NO_x burner. Parametric tests were conducted on a single 29 MW_t (100 x 10^6 Btu/hr) prototype burner to determine conditions required for low-NO_x operation and for combined NO_x/SO_2 control. SO_2 reduction was evaluated for two sorbents, two injection locations, and three coals. NO_x emissions of 150-250 ppm corrected to 3 percent O_2 were obtained under various combustion conditions. SO_2 reductions from 31 to 57 percent with no detrimental effect on NO_x emissions were observed.

INTRODUCTION

The thrust of the U.S. industrial energy program has been on the expanded use of coal in utility and industrial applications. However, 78% of the SO_2 and 44% of the NO_x emissions from man-made sources in the United States are produced by industrial and utility boiler fuel combustion(1). Because of this magnitude, and the apparent link between these emissions and acid rain, a good deal of combustion research and development has focused on SO_2 and NO_x control. The boiler industry, including the Riley Stoker Corporation, is actively engaged in this research and development. In order to advance emission control technology for pulverized coal boilers, Riley Stoker is developing new commercial burners and combustion systems for both utility and industrial applications.

Under a program sponsored by the U.S. Environmental Protection Agency (EPA), large pilot scale combustion tests were performed on a Riley Stoker Distributed Mixing Burner (DMB). These tests were conducted in the EPA's Large Watertube Simulator (LWS) furnace operated by the Energy and Environmental Research Corporation at their El Toro, California, test facilities. The objective of this program was to characterize a single 29 MW_t (100 x 10^6 Btu/hr) DMB under low NO_x operation, and to optimize the burner for combined NO_x/SO_2 control and acceptable operating conditions.

Low NO_x operation was established during baseline tests on a low sulfur Utah bituminous coal. In this operating mode the burner was staged to a burner zone stoichiometry of 70% of theoretical air while maintaining an overall total stoichiometry of 120%. Combined NO_x/SO_2 control tests were also conducted using dry sorbent injection. The sorbent test series included two sorbents injected at two locations.

The amount of sorbent injected was varied from a calcium to sulfur molar ratio (Ca/S) of 0.5 to 4.2. Following the baseline characterization tests on Utah coal, the burner was evaluated on both Indiana and Illinois high sulfur bituminous coals.

EPA LARGE WATERTUBE SIMULATOR

The LWS (Figure 1) was designed to simulate furnace conditions in utility boilers. The furnace is fired with a single burner mounted on the front wall. The furnace gas exit is located at the top on the rear wall. With this configuration, the gas flow pattern is similar to that in a wall-fired boiler. The furnace depth of 6.7 m (22 ft) is typical of pre-NSPS utility boilers with 29 MW_t (100 x 10^6 Btu/hr) burners.

The outer surface of the furnace is cooled by water sprays and is open to the atmosphere. In order to maintain thermal similarity with coal fired boilers, the flame zone of the furnace is refractory lined. The furnace wall in the immediate vicinity of the burner, however, is uncovered to ensure that the wall temperature near the burner will be cool as in field operation.

RILEY STOKER DISTRIBUTED MIXING BURNER

The Riley Stoker DMB, shown in Figure 2, is based on design criteria developed in previous U.S. EPA studies(2). It is a dual register burner with secondary air entering through two sets of radial swirl vanes. The two secondary air streams reach the throat of the burner through separate concentric air passages surrounding the coal nozzle. Although these two air passages would normally be incorporated in a common windbox, they were fed separately for this test program. This allowed independent flow measurement of each secondary air stream.

The burner was equipped with four tertiary air ports positioned around the periphery of the burner for staged combustion. These tertiary air ports are smaller and somewhat nearer the burner in the Riley Stoker

design than prescribed in the EPA's DMB criteria (2). We found that these design changes increased flame stability under deeply staged combustion conditions. The tertiary air ports were also equipped with inserts to further increase the tertiary air velocity and improve downstream air/fuel mixing.

In addition, the burner incorporates the venturi coal nozzle design developed for the Riley Stoker Controlled Combustion Venturi (CCV) burner (3). Both coal spreader and nozzle setback position were adjustable in the test burner.

SORBENT INJECTION SYSTEM

The sorbent injection system was designed to feed into two locations: the primary air stream after the pulverizer, and the tertiary air ports. Sorbent feed rate was controlled by a screw feeder. Premilled bulk sorbent was fed from a hopper to the screw feeder and into a compressed air stream. The sorbent was entrained by the compressed air and conveyed to the injection location. Sorbent was added to the primary air stream through a single nozzle downstream of the pulverizer. For injection through tertiary air ports, the sorbent was split into four streams and was injected through nozzles located on the axis of each tertiary air port.

COAL AND SORBENT ANALYSIS

Three bituminous coals, Utah, Indiana, and Illinois, were used in the program to determine the NO_x performance and SO_2 reduction potential of the burner. The Utah coal, with 0.7% sulfur, was used as the baseline test fuel. This coal is used in several other EPA LIMB (limestone injection multistage burner) programs. The high sulfur Indiana coal, with 2.5% sulfur, is also used in other LIMB programs. The Illinois coal, containing 3.5% sulfur, is currently fired in a large utility boiler retrofitted with Riley Stoker low NO_x CCV burners. A complete analysis of all three coals is shown in Table 1.

Two sorbents were evaluated in the test program: a commercially available limestone (Vicron 45-3), and a processed hydrated lime. The Vicron 45-3 limestone was 98-99% pure CaO_3 and had a mass median particle diameter of 11 μ m. The hydrated lime was 91-96% pure $Ca(OH)_2$ with a mass median particle diameter of 4-7 μ m. Analyses of these sorbents are shown in Table 2.

NO_x CONTROL

NO_x emissions as a function of burner zone stoichiometric ratio, SR_B, are summarized in Figure 3 for all three coals. The trends of NO_x versus SR_B were parallel for the Utah and Indiana coals. Utah coal consistently had the lowest NO_x emissions, while the Indiana coal had the highest emission level. Unstaged NO_x emissions of 360-430* ppm were reduced 40-45% to 200 - 250 ppm by reducing the burner zone stoichiometry to 0.7. Carbon monoxide (CO) emissions increased slightly at low burner zone stoichiometries. However, CO emissions never exceeded 40 ppm.

The effect of excess air or total furnace stoichiometric ratio, SR_T, on NO_x was examined for all three coals (Figure 4). At an SR_B of 0.7, both NO_x and CO were relatively insensitive to the total stoichiometry. Again, the slopes of NO_x versus SR_T for the Utah and Indiana coals were nearly identical. CO emissions from the Utah and Illinois coals were 20 - 25 ppm and showed no change with total stoichiometry. The CO emissions were generally 20 ppm higher for the Indiana coal than for the other two coals. Transient data showed a dramatic increase in CO for SR_T less than 1.1 for all three coals.

* All NO_x and CO concentrations reported at 3% O_2

Changes in furnace load had very little effect on NO_x or CO emissions under staged combustion conditions. NO_x dropped only 10-20 ppm when the firing rate was reduced to 60% load. Figure 5 shows the change in NO_x emissions with burner load under staged combustion conditions.

A number of burner design parameters were investigated before the above results were obtained with an optimized coal spreader design and constant diameter tertiary air ports. Several iterative spreader modifications were made to produce stable flames with acceptable flame lengths under deeply staged conditions. The effect of tertiary air velocity was investigated for the baseline Utah coal. Significantly decreasing tertiary air velocity by enlarging the ports from 20 to 30 cm diameter produced much longer flame lengths under deeply staged conditions. While the slower mixing produced by these larger ports resulted in slightly lower NO_x at comparable levels of staging, the resulting long flames were not viable in an acceptable operating condition for the LWS. The 20 cm diameter high velocity tertiary air ports, therefore, were used for the remainder of the testing.

SO_2 CONTROL

Sorbent injection tests were also conducted under staged combustion conditions for combined NO_x/SO_2 control on all three coals. Two sorbents were evaluated: limestone (Vicron 45-3) and hydrated lime. Sorbent was injected either with the coal or with the tertiary air. When injected with the coal, the sorbent was introduced downstream of the pulverizer.

Sulfur dioxide capture by sorbent injection is summarized in Figure 6 for each sorbent type, injection method, and test coal. Percent SO_2 reduction is displayed as a function of Ca/S molar ratio, sorbent

type, and injection location. Injection of hydrated lime with the tertiary air gave the best results with 48% sulfur capture at a Ca/S molar ratio equal to 2.0. Preliminary tests had shown that sulfur capture was only 30% at this Ca/S ratio when hydrated lime was injected with the coal.

There was very little difference in sulfur capture with injection location when limestone was used as the sorbent. Injection with the tertiary air gave slightly better results for Ca/S molar ratios less than 2 and slightly poorer results for Ca/S molar ratios greater than 2. Overall calcium utilization with lime through the tertiary ports was approximately 60 to 70% higher than limestone injection, for the range of Ca/S molar ratios tested.

Although the sulfur capture increased with increasing Ca/S molar ratio, calcium utilization dropped steadily for both sorbents with tertiary injection. During coal nozzle injection, limestone calcium utilization was independent of Ca/S molar ratio. This would suggest differences in the thermal histories of sorbent particles injected with the coal and with tertiary air.

Sorbent thermal history has a strong impact on sulfur capture. The ideal temperature window for the most favorable sulfation rates has been identified as 1200 to 800°C (2200 to 1500°F) (4). Gas temperatures measured with a suction pyrometer at the exit of the LWS ranged from 930 to 1010°C (1700 to 1850°F). Peak flame temperatures as high as 1270°C (2320°F) were measured within the flame under low NO_x firing conditions (i.e., SR_B = 0.7).

The percent SO_2 reduction was independent of the sulfur content of the fuel. This differs from previously reported pilot scale results (5,6). In these studies the percent sulfur capture increased as the

sulfur content of the fuel increased. This may be caused by changes in burner and furnace design. The work by Ohmine et al. (6), which showed a much larger dependence on sulfur content, was done in a tangential furnace.

Finally, sorbent injection had little effect on NO_x emissions. NO_x emissions and flame characteristics were much more sensitive to changes in burner settings than was SO_2 reduction. Consequently, the burner was set for minimum NO_x emissions for all the sorbent injection tests. The average NO_x emissions at SR_B of 0.7 with and without sorbent injection are shown in Table 3. The change in NO_x emissions was very small and well within the data scatter.

FLY ASH CHARACTERISTICS

Sorbent injection can cause changes in the furnace fly ash characteristics. Furnace fly ash samples, therefore, were collected for selected test conditions and subjected to laboratory analysis. Fly ash characteristics with and without sorbent injection are summarized in Table 4.

Ash fusibility or melting behavior is one indicator of the tendency for coal ash to slag or foul furnace tube surfaces. For the Utah coal, the initial ash deformation temperature under reducing conditions dropped from 1263°C (2305°F) to 1146°C (2095°F) with limestone injected through the tertiary air ports. A reducing atmosphere is normally used to determine laboratory ash fusion temperatures since it more closely represents conditions in the high heat release regions of the developing flame zone. The initial deformation temperature for the Indiana and Illinois coals remained essentially unchanged at 1170°C (2140°F).

The ash softening temperature of the Utah coal dropped to 1191°C (2175°) from 1316°C (2400°F). However, the softening temperatures showed little or no change for the Indiana and Illinois coals, remaining at 1238°C (2260°F) and 1200°C (2200°F), respectively. The softening temperature is the fusibility temperature most often used to evaluate fouling and slagging.

The ash fluid temperature decreased due to limestone addition for all three coals. The lowest ash fluid temperature was exhibited by the Illinois coal, decreasing from 1307 to 1196°C (2385 to 2185°F) with limestone addition.

Another indicator which has been used to characterize ash behavior is the difference between the initial deformation temperature and fluid temperature (7). As the temperature difference narrows the deposits may become more difficult to remove. This temperature difference became smaller for all three coals tested. The behavior of ash particles in an actual boiler, however, is complicated by combustion conditions, as well as the variability of coal properties. For example, recent pilot scale tests in a fouling and slagging test rig found that furnace wall deposits for an Illinois No. 6 coal became easier to remove with limestone addition (8). In applying this technology, ash deposition within a boiler must be evaluated on a case by case basis.

SUMMARY

Limestone injection with multistage burners (LIMB) can provide significant reductions in SO_2 emissions while maintaining low NO_x emissions using the Riley Stoker Distributed Mixing Burner. Under optimum operating conditions the burner exhibited:

- NO_x emissions of 200-250 ppm corrected to 3% O_2 at full load under staged combustion conditions (SR_B=0.7).

- NO_x emissions of 150-200 ppm corrected to 3% O_2 at 60% burner load under staged combustion conditions (SR_B=0.7).

- SO_2 reduction of 45-57% with hydrated lime through tertiary air ports (Ca/S=2.0).

- SO_2 reduction of 31-33% with limestone injected through tertiary air ports (Ca/S=2.0).

- SO_2 reduction of 32-35% with limestone injected through the coal nozzle (Ca/S=2.0).

- No detrimental effects on NO_x emissions during injection of calcium based sorbents at the burner.

Sorbent injection can have a large impact on boiler operation by changing the ash loading and ash characteristics. Table 5 shows how addition of sorbent can affect the ash loading for each of the three coals tested. Increasing the ash loading of the flue gas may increase fouling of convection tubes and air heater. The reduction in ash fusion temperatures may also be a problem, increasing the potential for slagging in the flame zone. Studies are underway to assess these potential problems and to understand the characteristics of ash which has been exposed to sorbent injected in the boiler.

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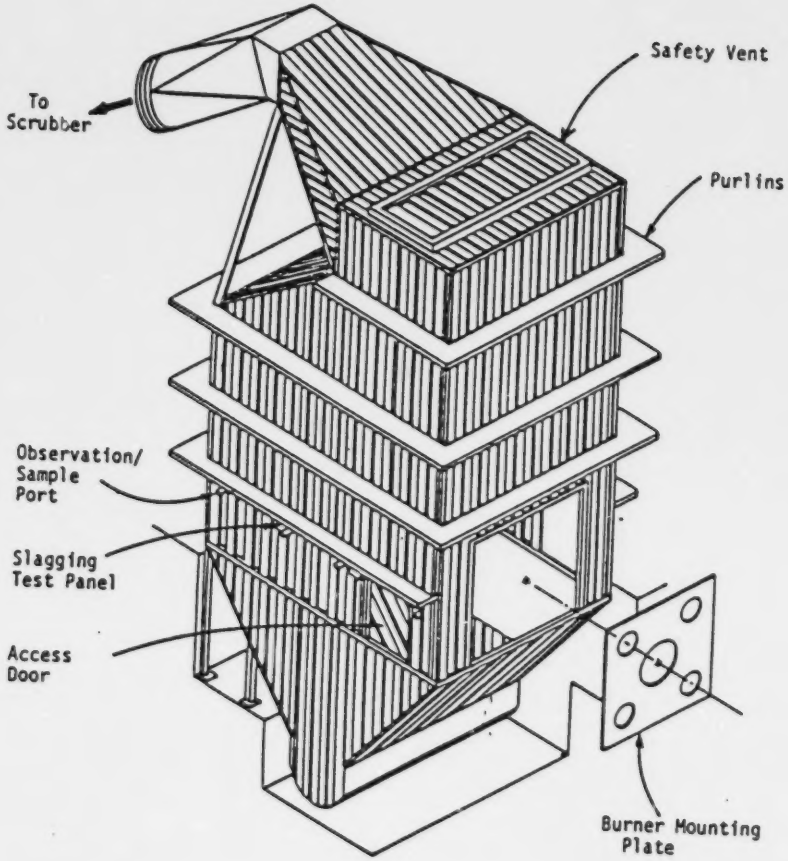

FIRING DEPTH
6.7 m (22 ft)

WIDTH
4.9 m (16 ft)

OVERALL HEIGHT
15.4 m (50.5 ft)

WALL FIRED

PARTIAL INSULATION

SPRAY COOLED

Figure 1 EPA Large Watertube Simulator (LWS)

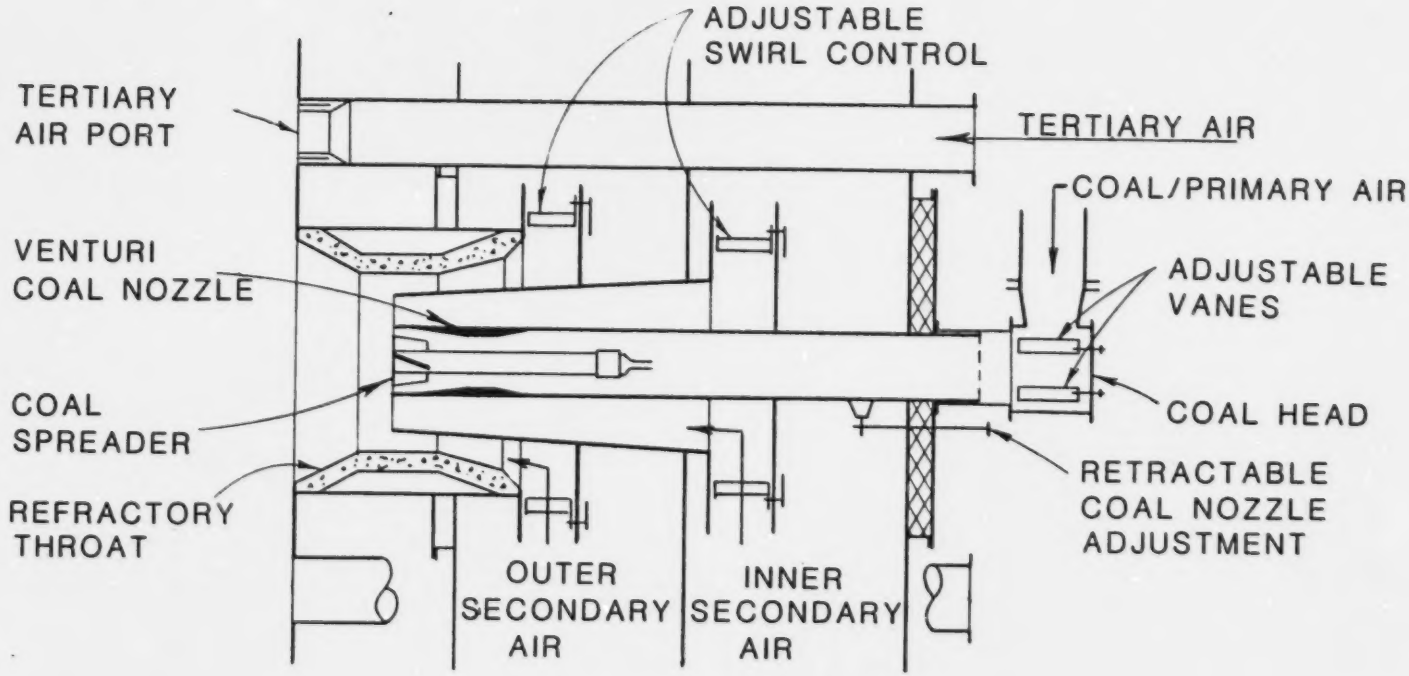

Figure 2 Riley Stoker Distributed Mixing Burner (DMB)

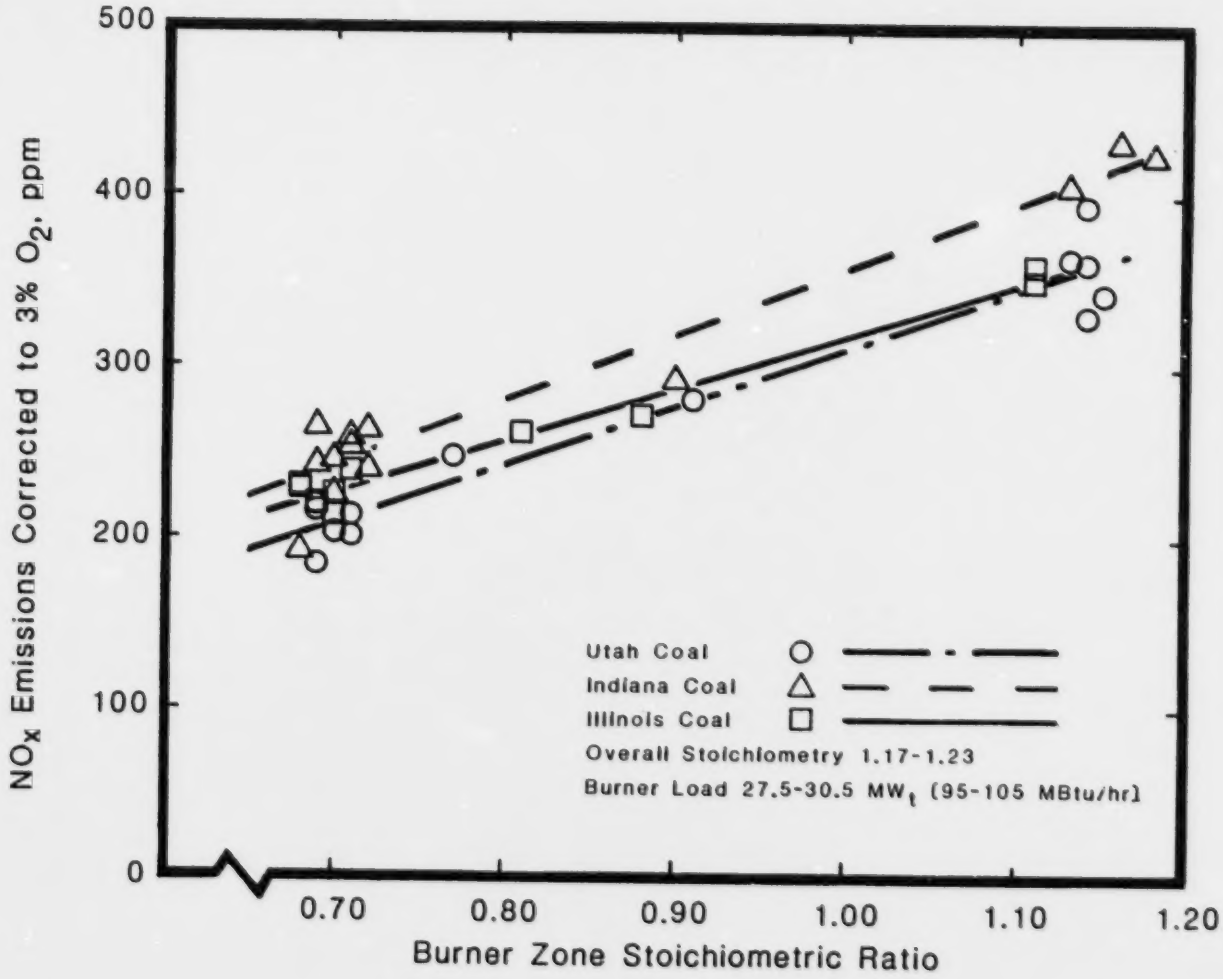

Figure 3 Effects of Burner Zone Stoichiometric Ratio on Performance of the Riley Stoker DMB

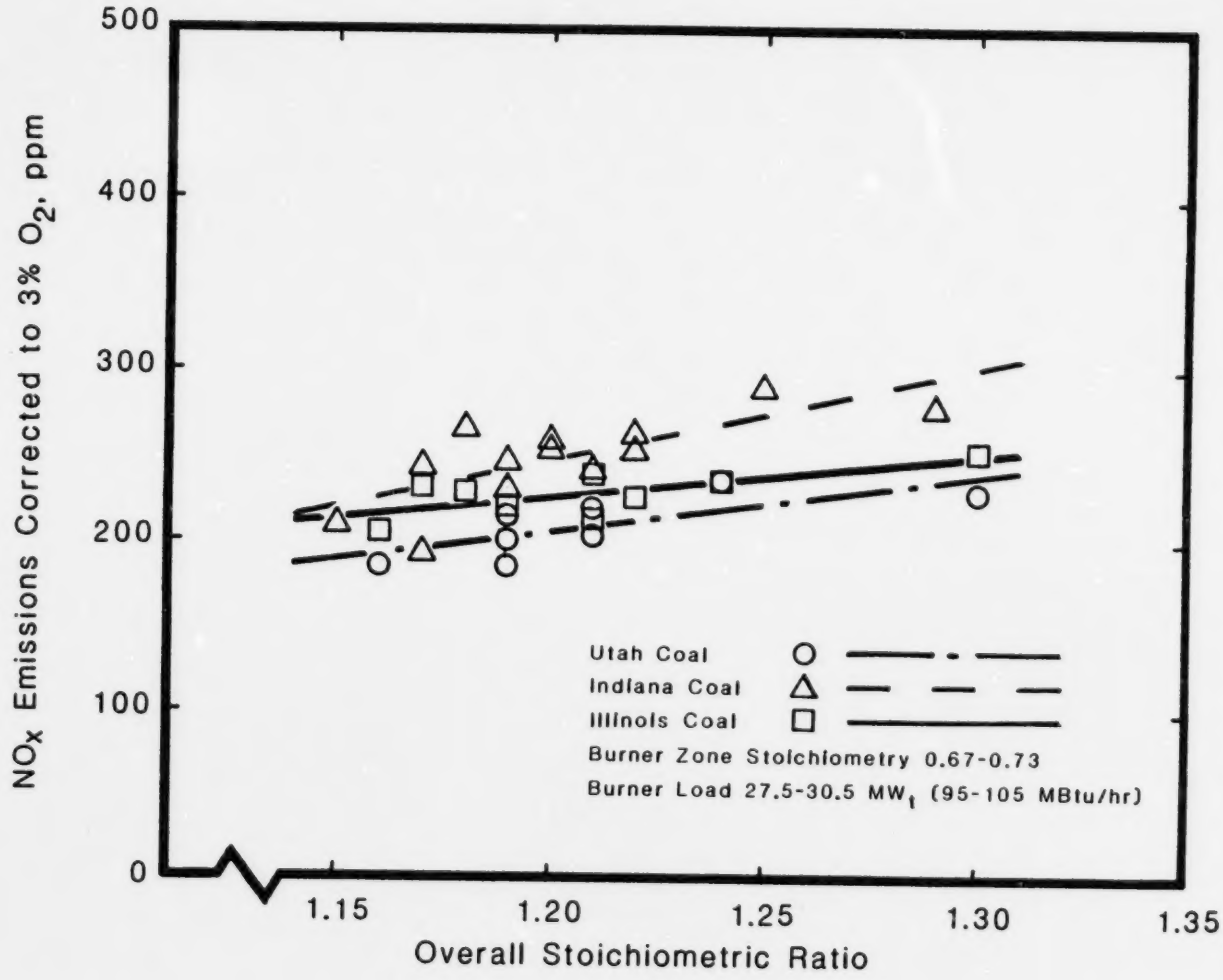

Figure 4 Effects of Overall Stoichiometric Ratio on Performance of the Riley Stoker DMB

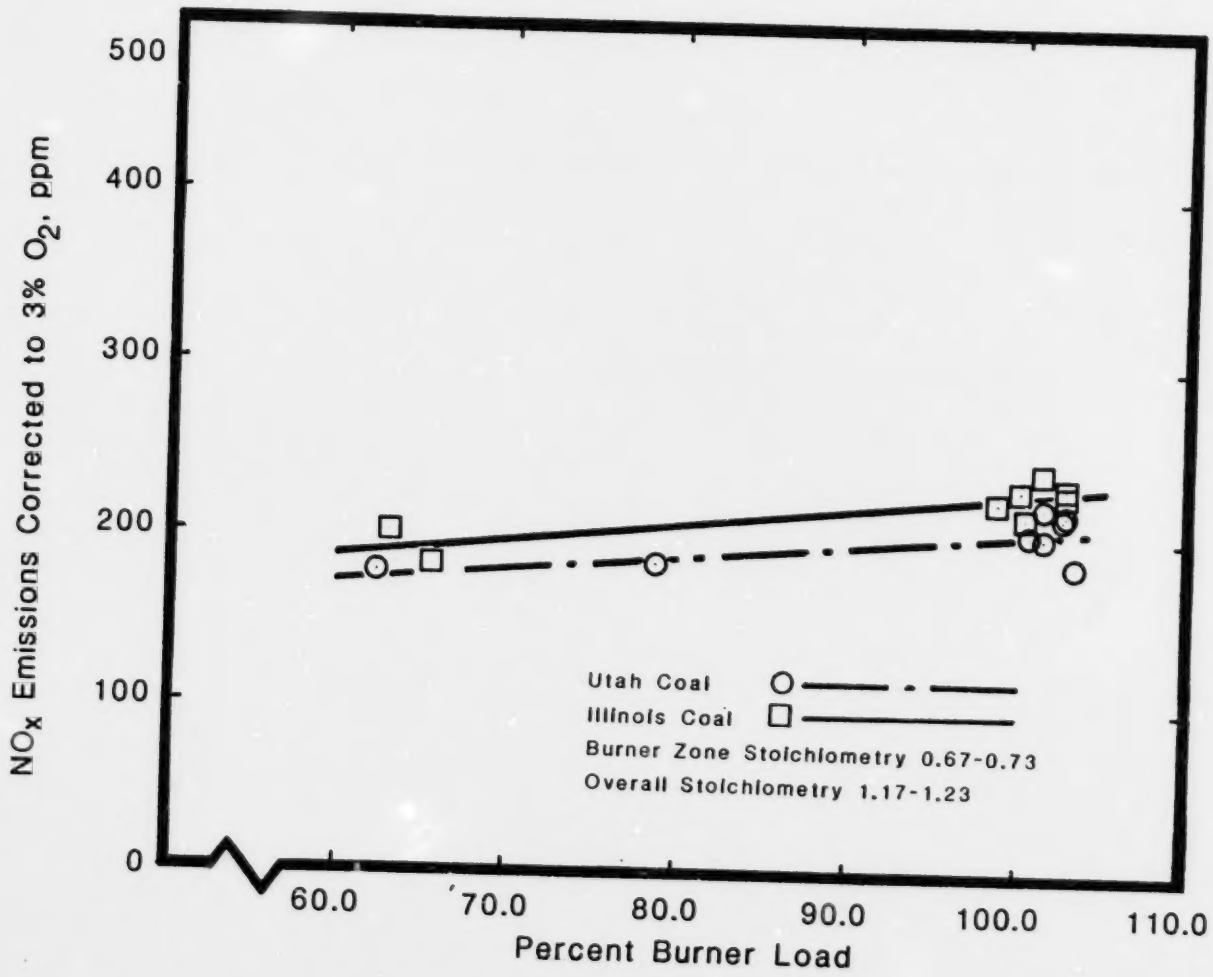

Figure 5 Effects of Burner Load on Performance of the Riley Stoker DMB

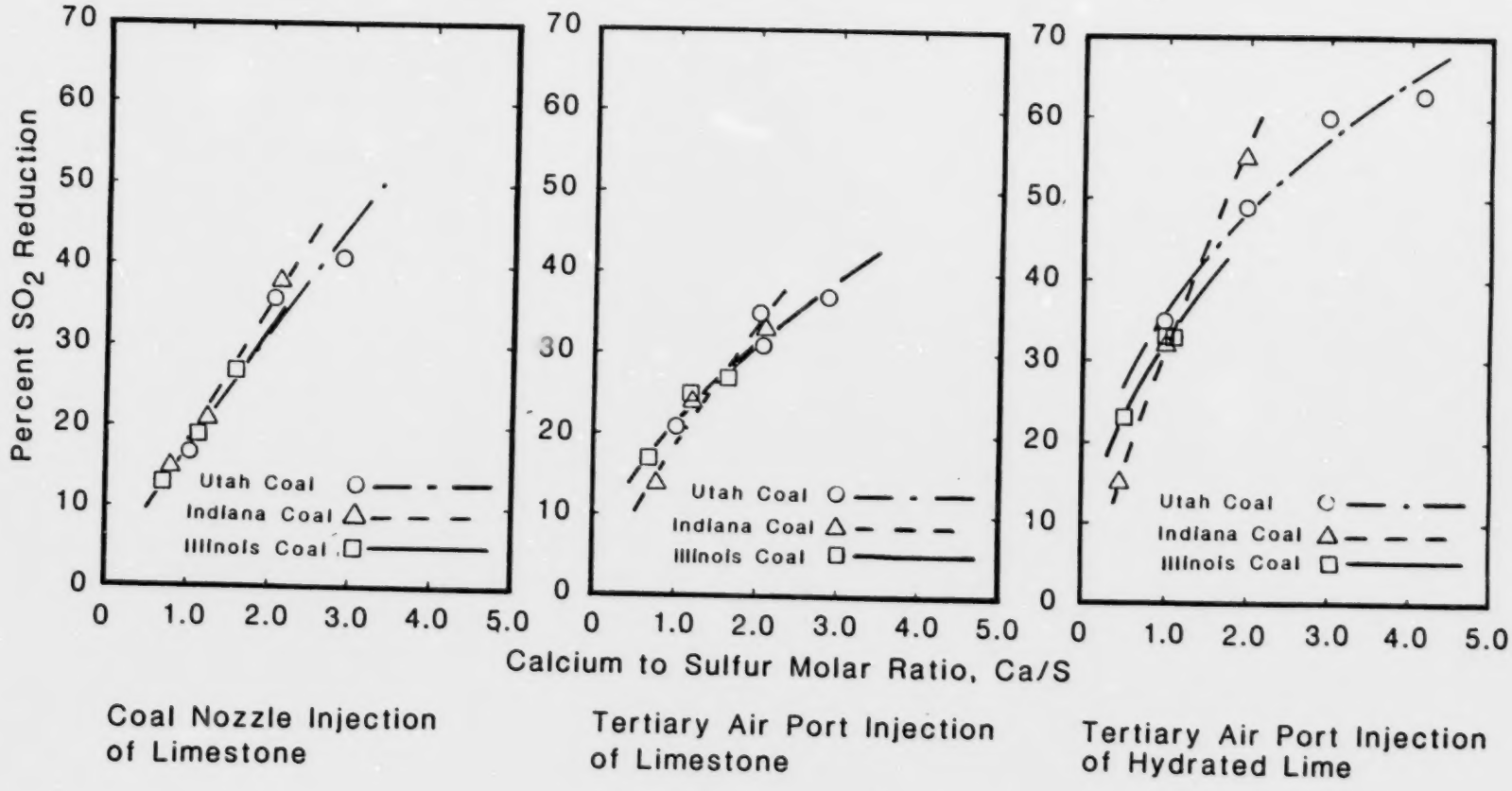

Figure 6 Sulfur Capture Potential with the Riley Stoker DMB

TABLE 1 SUMMARY OF COAL COMPOSITION

Reporting Basis	Utah Coal		Indiana Coal		Illinois Coal	
	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Proximate (% Wt)						
Moisture	5.46	0.00	7.75	0.00	10.66	0.00
Ash	10.00	10.57	9.17	9.94	9.37	10.49
Volatile	38.26	40.47	31.60	34.26	34.51	38.62
Fixed Carbon	46.28	48.96	51.48	55.80	45.46	50.89
Total	100.00	100.00	100.00	100.00	100.00	100.00
Sulfur	0.70	0.74	2.52	2.73	3.54	3.97
HHV MJ/kg(Btu/lb)	27.74(11930)	29.35(12619)	26.74(11498)	28.99(12465)	26.20(11265)	29.32(12609)
MMF MJ/kg(Btu/lb)		33.18(14269)		32.67(14048)		33.37(14349)
MAF MJ/kg(Btu/lb)		32.82(14111)		32.19(13841)		32.76(14086)
Ultimate (% Wt)						
Moisture	5.46	0.00	7.75	0.00	10.66	0.00
Carbon	67.59	71.50	66.42	72.00	61.99	69.38
Hydrogen	5.09	5.38	4.56	4.95	4.54	5.08
Nitrogen	1.21	1.28	1.10	1.19	0.96	1.08
Sulfur	0.70	0.74	2.52	2.73	3.54	3.97
Ash	10.00	10.57	9.17	9.94	9.37	10.49
Oxygen	9.95	10.53	8.48	9.19	8.94	10.00
Total	100.00	100.00	100.00	100.00	100.00	100.00
Elemental Ash (% Wt)						
SiO_2		66.17		43.08		49.45
Al_2O_3		16.49		23.79		17.28
TiO_2		0.68		0.49		0.68
Fe_2O_3		4.95		27.85		18.41
CaO		3.72		1.16		4.33
MgO		0.87		0.20		0.83
Na_2O		1.27		0.17		1.40
K_2O		2.11		0.65		2.15
P_2O_5		0.30		0.22		0.18
SO_3		3.07		0.19		4.31

TABLE 2
SUMMARY OF SORBENT CHARACTERISTICS

Sorbent	Theoretical Characteristics	Physical Properties				Chemical Analysis (% Weight)							
		Mean Size (μm)	Density g/cm^3 (lb/ft^3)	Surface Area m^2/g(ft^2/lb)	Ignition Loss % Wt. @ 1093°C(2000°F)	CaO	Fe_2O_3	Al_2O_3	Na_2O	MgO	K_2O	SiO_2	Cr_2O_3
Vicron 45-3	$CaCO_3$	11.0	2.757(172.1)	0.9(4402)	44.0	54.8	0.106	0.13	0.030	0.804	0.013	0.15	0.009
Hydrated Lime	$Ca(OH)_2$	7.0	2.353(146.9)	10.4(50866)	26.4	68.4	0.469	0.53	0.046	0.423	0.155	2.31	0.007

TABLE 3

NO_x EMISSIONS WITH AND WITHOUT SORBENT

	NO_x (ppm @ 3% O_2)		
	Utah	Indiana	Illinois
With Sorbent	228 ± 11	246 ± 11	203 ± 9
Without Sorbent	223 ± 11	245 ± 20	195 ± 14

TABLE 4

ASH CHARACTERISTICS WITH VICRON INJECTED THROUGH THE TERTIARY AIR PORTS

Item	Utah Coal		Indiana Coal		Illinois Coal	
Ca/S Molar Ratio	---	2.13	---	1.38	---	1.65
Load MW_t(MBtu/hr)	29.9(102.1)	28.5(97.4)	29.1(99.3)	30.2(103.0)	30.1(102.7)	28.7(97.8)
SR_B	0.69	0.71	0.72	0.71	0.70	0.70
SR_T	1.19	1.22	1.21	1.20	1.22	1.21
% SO_2 Capture	---	27	---	291	---	27
C %	10.0	8.0	8.0	3.7	6.2	2.8
S %	0.7	1.3	2.1	2.1	2.8	4.8
Ash %	88.1	90.5	90.7	95.0	92.7	95.3
CaO %	7.4	20.8	5.6	18.2	10.4	31.0
SO_3 %	1.9	6.3	3.8	5.4	5.9	13.1
IDT(Red)°C(°F)	1263(2305)	1146(2095)	1171(2140)	1166(2130)	1171(2140)	1168(2135)
ST (Red)°C(°F)	1316(2400)	1191(2175)	1238(2260)	1246(2275)	1210(2210)	1177(2150)
HT (Red)°C(°F)	1393(2540)	1210(2210)	1324(2415)	1266(2310)	1252(2285)	1182(2160)
FT (Red)°C(°F)	1449(2640)	1307(2385)	1382(2520)	1313(2395)	1307(2385)	1196(2185)

IDT - Initial Deformation Temperature
ST - Softening Temperature, H=W
HT - Hemispherical Temperature, H= 1/2 W
FT - Fluid Temperature

TABLE 5

EFFECTS OF COAL TYPE AND SORBENT INJECTION
ON FLUE GAS ASH LOADING [a]

Ash Loading ng/J (lb/10^6 Btu)

Ca/S	Utah Coal		Indiana Coal		Illinois Coal	
Molar Ratio	Limestone	Hydrated Lime	Limestone	Hydrated Lime	Limestone	Hydrated Lime
0	3600(8.37)	3600(8.37)	3420(7.96)	3420(7.96)	3640(8.47)	3640(8.47)
1	4170(9.69)	4300(10.0)	5430(12.6)	5820(13.5)	6760(15.7)	7330(17.0)
2	4710(10.9)	4850(11.3)	7450(17.3)	8150(19.0)	9640(22.4)	10360(24.1)
3	5230(12.2)	5390(12.5)	9447(22.0)	10500(24.4)	12450(29.0)	13330(31.0)

a. tertiary air injection